Appendix J

Transfer Factors

Appendix J

Transfer Factors

J-1. INTRODUCTION

The purpose of this section is to summarize the plant uptake factors (PUFs) and transfer factors (TFs) used in the WAG 4 ERA. Both organic and inorganic contaminants have been identified at WAG 4 sites. The approach for developing PUFs and other TFs for use at the INEEL was different for each type of contaminant is presented in the next following sections.

J-1.1 Plant Uptake Factors for Inorganics

The overall summaries and the values provided by such comprehensive papers such as Baes et al. (1984), IAEA (1994), Ng et al. (1979), and EPA (1989) were given preference in selecting PUFs. These studies are well documented and accepted by the decision-makers. Additional studies on native or other grass PUFs identified were given the highest priority, since several investigators have noted the highest Pu concentration in native grasses (Hakonson 1975). Documentation of this effort is presented in the OU 10-04 work plan, currently in draft.

Table J-1 provides a summary of published values for plant/soil concentration ratios for inorganic contaminants. This summary is based on chemical element rather than specific radionuclide; and as such, ignores any potential isotope effects. Four publications (Baes et al., 1984; IAEA, 1994; EPA, 1989; Ng et al., 1979) provide the focus for these values. Concentration rates (CRs) provided by other publications evaluated are provided in a separate column. The best estimate for use in INEEL ERAs is provided for each element.

J-1.2 Plant Uptake Factors for Organics

The PUFs for organics were calculated using an allometric equation presented in Travis and Arms (1988). This equation is as follows:

$\log PUF = 1.588\text{-}0.578 \log K_{ow}$.

Log partitioning coefficients (K_{ow}s) were taken from Montgomery and Welkom (1990).

PUFs outside the range assessed in the Travis and Arms study (1988) were assigned values at the limits of the evaluation. Table J-2 presents the values for organics identified as present at WAG 4 sites calculated using the allometric equation.

J-1.3 Transfer Factors to Herbivores for Inorganics

With some exceptions, literature supports the development of TFs for meat and dairy products (primarily herbivores) reflecting the emphasis placed on human health. For inorganic contaminants, this information is summarized in several sources including; IAEA (1994), Ng et al. (1979), EPA (1989), and NCRP (1984). These were evaluated as well as any additional studies that were available and the most applicable TFs was selected. As shown in Table J-3, the overall summaries and the values provided by comprehensive TF were given some preference in the selection process since these studies are well documented and accepted by decision-makers.

Table J-1. Plant uptake factors used in the WAG 4 risk assessment for inorganic contaminants.

Element	Baes et al. (B4)	IAEA (I2)	EPA (E3)	Ng et al. (N1)	Other Sources	Suggested for Crops	Suggested, INEEL Native Plants
Antimony (Sb)	2.0E-01	2.0E-01	5.6E-04 (root)	—	1.2E-01 (D1)	5.6E-04 (I2)	2.0E-01
Arsenic (As)	4.0E-02	4.0E-02	—	—	1.3E-02	4.0E-02 (B4)	4.0E-02 (B4, D1)
Barium (B)	1.5E-01	1.5E-01	3.0E-02 (not specified)	5.1E-02 (1.8E-02 to 8.3E-02)	—	3.0E-02 (I2)	1.5E-01 (B4)
Cadmium (Cd)	5.5E-01	5.5E-01	—	—	—	5.5E-01 (B4)	5.5E-01 (B4)
Chromium (Cr)	7.5E-03	7.5E-03	1.0E-03 (not specified)	2.9E-02 (3.6E-03 to 8.5E-02)	1.9E-01 (D1)	1.0E-03 (I2)	1.9E-01 (D1)
Cobalt (Co)	2.0E-02	2.0E-02	3.73E-03 to 1.1 (alfalfa)	2.4E-01 (8.0E-03 to 1.1)	1.0E-01 (D1)	2.9E-01 (spinach, I2)	1.1 (I2)
Copper (Cu)	4.0E-1	4.0E-1	8.0E-01	6.7E-01 (5.1E-02 to 1.9)	3.6E-01 (D1)	8.0E-01 (I2)	8.0E-01 (I2, D1)
Lead (Pb)	4.5E-02	4.5E-02	1.1E-03 to 2.0E-02 (root)	—	—	2.0E-02 (I2)	2.0E-02 (I2)
Manganese (Mn)	2.5E-01	2.5E-01	4.7E-02 to 9.8 (alfalfa)	2.6 (4.2E-02 to 2.0)	—	1.9 (I2, carrot)	9.8 (I2)
Mercury (Hg)	9.0E-01	9.0E-01	—	—	—	9.0E-01 (B4)	9.0E-01 (B4)
Selenium (Se)	2.5E-02	2.5E-02	—	—	1.7 (D1)	2.5E-02 (B4)	2.5E-02 (B4)
Silver (Ag)	4.0E-01	4.0E-01	2.7E-04 TO 1.5E-01 (not specified)	—	—	1.5E-01 (I2)	4.0E-01 (B4)
Sodium (Na)	7.5E-02	7.5E-02	3.0E-01 (not specified)	7.0E-02 (no range)	—	3.0E-01 (I2)	3.0E-01 (I2)
Thallium (Tl)	4.0E-03	4.0E-03	—	—	—	4.0E-03 (B4)	4.0E-03 (B4)
Vanadium (V)	5.5E-03	—	—	—	5.5E-04 (D1)	5.5E-03 (B4)	5.5E-03 (B4)
Zinc (Zn)	1.5	1.5	5.6E-01 to 35 (potato)	9.3E-01 (1.2E-01 to 4.4)	—	35 (I2)	35 (I2)

Table J-2. Plant uptake factors used in the WAG 4 risk assessment for organic contaminants.

CAS #	Contaminant	K_{ow}	Calculated PUF	PUFs used in ERA
67-64-1	Acetone	5.75E-01	5.33E+01	5.33E+01
50-32-8	Benzo(a)pyrene	1.15E+06	1.22E-02	1.22E-02
205-99-2	Benzo(b)fluoranthene (BbF)	1.15E+06	1.22E-02	1.22E-02
191-24-2	Benzo(g,h,i)perylene	3.24E+06	6.68E-03	6.68E-03
207-08-9	Benzo(k)fluoranthene	1.15E+06	1.22E-02	1.22E-02
218-01-9	Chrysene	4.07E+05	2.22E-02	2.22E-02
53-70-3	Dibenzo(a,h)anthracene	6.31E+06	4.55E-03	
193-39-5	Indeno(1,2,3)pyrene	3.16E+06	6.78E-03	6.78E-03
11097-69-1	Aroclor 1254	1.07E+06	1.3E-02	1.3E-02
	TPH	—	—	1.0E+00
1330-20-7	Xylene (mixed)	1.83E+03	5.0E-01	5.0E-01

Table J-3. Transfer factors (for herbivores) for inorganic contaminants at WAG 4.

	Baes et al.[a] (1984)	EPA (1989[a])	NCRP (1984)	Ng et al. (1979)	IAEA (1994)[a]	Other Sources	Suggested for INEEL
Antimony (Sb)	1.0E-03	2.0E-01	4.0E-03	1.2E-03	4E-05 (beef)		2.0E-01
Arsenic (As)	2.0E-03	4.0E-02	Not given	Not given			4.0E-02
Barium (Ba)	1.5E-04	1.5E-01	3.2E-03	1.6E-04	2E-04 (beef) 9E-03 (poultry)	Hope & Miller (1996) found that Ba bioaccumulation factors are low for all terrestrial receptors examined and the concentrations decrease in increasing trophic levels. Johnson et al., 1988 2.3E-04 (cow), 1.3E-05 (goat)	1.5E-01
Cadmium (Cd)	5.5E-04	5.5E-01	Not given	Not given	1.5E-02 (pork) 8E-01 (poultry)	Laurinolli & Bendel-Young (concentrations in liver) 0.47 (reference area) to 0.27 (Cu mine site). This is a temperate site.	5.5E-01
Chromium (Cr)	5.5E-03	7.5E-03	2.4E-03	5.6E-03	9E-03 (beef)		7.5E-03
Cobalt (Co)	2.0E-02	2.0E-02	1.3E-02	2.1E-02	6.2E-02 (sheep) 2 (poultry)		2.0E-02
Copper (Cu)	1.0E-02	4.0E-01	8.0E-03	1.1E-02	3.9E-02 (sheep) 5E-01 (poultry)	Laurinolli & Bendel-Young (1996) (concentrations in liver) 0.53 (reference area) to 0.12 (Cu mine site). This is a temperate site.	4.0E-01
Lead (Pb)	3.0E-04	4.5E-02			4E-04 (beef)	Pb-210 beef fraction element ingested daily in kg of flesh 2E-04 to 2E-03 (Chester and Garten 1980)	4.5E-02
Manganese (Mn)	4.0E-04	2.5E-01	8.0E-04	3.9E-04	5.9E-03 (sheep) 5E-02 (poultry)		2.5E-01
Mercury (Hg)	2.5E-01	9.0E-01			3E-02 (poultry)		9.0E-01
Nickel							
Nitrate							
Selenium (Se)	1.5E-02	2.5E-02			3.2E-01 (pork) 9 (poultry)		3.2E-01
Silver (Ag)	3.0E-03	4.0E-01	1.7E-02	2.9E-03	2E-02 (pork) 2.0E+00 (poultry)		4.0E-01
Thallium (Tl)	4.0E-02	4.0E-03	Not given	Not given			4.0E-02
Vanadium (V)	2.5E-03	Not given	Not given	Not given			
Zinc (Zn)	1.0E-01	1.5E+00	Not given	Not given	4.1 (sheep) 7.0E+00 (poultry)	Laurinolli & Bendel-Young (1996) (concentrations in liver) 1.16 (reference area) to 0.66 (Cu mine site). This is a temperate site.	1.5E+00

J-1.4 Transfer Factors to Herbivores for Organics

The TFs for organics were calculated using the following allometric equation presented in Travis and Arms (1988):

$\log TFs = -7.6 + \log K_{ow}$.

Log partitioning coefficients (K_{ow}s) were taken from Montgomery and Welkom (1990).

TFs outside the range of the Travis and Arms (1988) study were assigned values at the limits of the evaluation. Table J-4 presents the values for organics identified as present on the INEEL as calculated using the allometric equation. This equation presents the tissue concentration.

J-1.5 Transfer Factors to other Trophic Levels for Inorganics

Data are lacking for TFs for insectivores, omnivores and carnivores. At the WAG ERA level, these TFs were defaulted to 1.0. This is considered a conservative assumption. Some effort was made to evaluate biotransfer of selected metals in these different trophic levels. This effort resulted in allowing more specific information to be incorporated into the risk assessment. The general pattern of metals accumulation in soil invertebrates is toward higher concentrations in spiders (*Arachnida*) and detritivores than in herbivorous and carnivorous species (Stafford 1988; Ainsworth 1990a). Because earthworms are an important link in the food chains of insectivorous and carnivorous animals, their uptake of soil-associated chemicals has been more extensively studied than that of other terrestrial soil-dwelling invertebrates. Earthworms at INEEL occur only on irrigated lawns but may be used as an example of invertebrate bioaccumulation. In general, earthworms may provide a good indication of the "worst case" of metal uptake by soil-dwelling invertebrates (Stafford 1988). Thus, TFs for earthworms may be regarded as a conservative surrogate for other invertebrates. Further, accumulation of certain metals in insectivorous mammals reflects their bioavailability to earthworms (Ma 1987; Scanlon 1987; Hegstrom and West 1989).

The relatively well-studied earthworm system demonstrates some of the complexities of predicting the biotransfer of metals in terrestrial ecosystems. The body concentration of a metal in earthworms is determined by its concentration in soil, the intrinsic rate of bioaccumulation, and the tolerance of the organism to the element. It also depends on the influence of several edaphic factors, notably soil pH, organic matter content, calcium content, and cation exchange capacity (CEC) (Ma 1982; Ma et al. 1983; Corp and Morgan 1991). The bioavailability of several metals to worms appears to be greater in sandy than loamy soils (Ma 1982).

CEC, the total amount of cations exchangeably adsorbed by the soil exchange complex, provides an estimate of the capacity of the soil to adsorb heavy metals and gives a measure of the ability of soils to retain these metals against uptake by earthworms (Ma 1982). Significant negative correlations were found between the concentration factor (CF) and the pH of the soil for several metals, including zinc (Ma 1982). For copper, a negative correlation was found with soil organic matter (Ma 1982). Further, the presence and concentration of other metals can have a significant effect on worm uptake of particular metals (Back 1990).

In view of the many gaps in our knowledge of metal biotransfer in the terrestrial environment, the TFs for the metals in the following subsection are highly uncertain. An effort has been made to select factors that are protective for use in the assessments at INEEL. All of these values are in terms of dry weight. The results of this effort are provided in Table J-5.

Table J-4. Transfer factors (for herbivores) for organic contaminants at WAG 4.

CAS #	Contaminant	K_{ow}	Calculated TF
67-64-1	Acetone	5.75E-01	1.44E-08
50-32-8	Benzo(a)pyrene	1.15E+06	2.89E-02
205-99-2	Benzo(b)fluoranthene (BbF)	1.15E+06	2.89E-02
191-24-2	Benzo(g,h,i)perylene	3.24E+06	2.89E-02
207-08-9	Benzo(k)fluoranthene	1.15E+06	8.14E-02
218-01-9	Chrysene	4.07E+05	1.02E-02
53-70-3	Dibenzo(a,h)anthracene	6.31E+06	1.59E-01
193-39-5	Indeno(1,2,3)pyrene	3.16E+06	7.94E-02
11097-69-1	Aroclor 1254	1.07E+06	2.69E-02
1330-20-7	Xylene (mixed)	1.83E+03	4.60E-05

Table J-5. PUFs and TFs (or CFs) for selected WAG 4 inorganic contaminants[a] (unitless).

Contaminants	PUF[b]	TF[c] for Insectivores	TF for Carnivores[e]	TF for Omnivores[f]
Antimony	2.0E-01	9.0E-01	5.5E-03	9.0E-01
Arsenic	4.0E-02	1.0E+00	4.0E-02	1.0E+00
Cadmium	5.5E-01	1.1E+00	1.9E+00	1.9E+00
Chromium	1.9E-01	6.0E-02	2.0E-01	2.0E-01
Copper	4.0E-01	1.0E+00	2.0E-01	1.0E+00
Lead	4.5E-02	3.0E-01	6.0E-01	6.0E-01
Mercury	9.0E-01	4.0E-01	7.0E-01	7.0E-01
Zinc	1.5E+00	1.0E+00	7.0E-01	1.0E+00

a. Values and or literature for inorganics come from Baes et al., (1984).

b. PUF = Plant uptake factor, appropriate for use with AV100 and M100 Functional Groups.

c. Transfer factor.

d. TFs or CFs for insectivores, appropriate for AV200 and M200 Functional Groups.

e. TFs or CFs for carnivorous, appropriate for AV300 and M300 Functional Groups.

f. TFs or CFs for omnivores, appropriate for AV400 and M400 Functional Groups.

J-1.5.1 Metals Analysis

J-1.5.1.1 Antimony. The biotransfer of antimony within food chains in a grassland ecosystem in the vicinity of an antimony smelter was studied by Ainsworth (1990a,b 1991). Several mammalian and macroinvertebrate species at different trophic levels, as well as food plants, were examined in areas with soil concentrations of antimony ranging from 6.9 mg/kg (Ainsworth 1990b) to 386 mg/kg near the smelter. Tissue concentrations in all species examined were low relative to both soil and dietary concentrations, indicating that for antimony bioaccumulation in potential terrestrial food chains is low.

The general trend for invertebrates was toward higher concentrations in the detritivores (oligochaetes, diplopods, isopods, and dipteran larvae) than in the herbivorous and predatory groups (e.g., lepidopterans and staphylinids). This trend indicates a pattern of food chain biominification for this metal. As shown in Table J-6, mean TFs ranged from 0.04 in lepidopterans to 0.9 in oligochaeta (Ainsworth 1990b), with a geometric mean for all macroinvertebrates of 0.1.

Two herbivorous species (the rabbit [*Oryctolagus cuniculus]* and the short-tailed field vole [*Microtus agrestis]* and one insectivorous species (the common shrew [*Sorex araneus]*) of mammals were examined as available at the study locations. Antimony concentrations were measured in individual organs rather than the whole body, limiting the usefulness of these data for purposes of estimating food chain exposure. To ensure that bioaccumulation is not underestimated, TFs were calculated with data from the liver, which contained the highest concentrations of antimony in all species. Results are shown in Table J-7. Although these TFs are clearly overestimated because antimony concentrations in liver are undoubtedly higher than whole-body concentrations, they are still considerably less than unity, indicating no biomagnification of antimony in small mammals. However, the insectivorous shrew appeared to accumulate more antimony than the herbivorous species, perhaps due to greater bioavailability of invertebrate-borne metal (Ainsworth 1990b). The geometric mean TF for the three species was approximately 0.002. A TF of 1.0 was used for all functional groups to be protective at the screening level.

J-1.5.1.2 Cadmium. Large differences in cadmium concentrations among arthropod and mammalian species collected at the same site have been observed. Laskowski (1991) summarized available data on cadmium bioaccumulation in terrestrial food chains. Organisms considered included macroinvertebrates and the carnivorous shrew (S. araneus), and encompassed four trophic levels: herbivores, carnivores, top carnivores, and detritivores. Of 37 reported tissue:dietary concentration ratios identified in the literature for cadmium, 26 were greater than 1.0 (Laskowski 1991). Geometric mean values for herbivorous, carnivorous, and detritivorous invertebrates were 1.1, 1.5, and 2.4, respectively. The mean tissue:diet ratio for the shrew was 1.7 (Laskowski 1991). However, the slope of the regression line of dietary to tissue concentrations for all species was only slightly greater than 1.0 (1.3), indicating little potential for biomagnification in the terrestrial food chain. These data, summarized in Table J-8 were used to estimate the following TFs for terrestrial organisms.

Assuming a plant uptake factor (PUF) of 0.55 for cadmium (Baes et al. 1984), a geometric mean tissue-to-soil TF ratio of 0.6 can be estimated for herbivorous invertebrates by multiplying the two factors:

$$Herbivorous\ Invertebrate_{BAF\ cadmium} = PUF_{cadmium}\ x\ \frac{[Cadmium]\ in\ invertebrate}{[Cadmium]\ in\ plants} \qquad \text{(J-1)}$$

Table J-6. Mean TFs for antimony in terrestrial macroinvertebrates.[a]

Taxonomic group	Mean TF (± SD)
Isopoda	0.13 ± 0.13
Diplopoda	0.13 ± 0.12
Lepidoptera	0.04 ± 0.02
Diptera	0.20 ± 0.07
Coleoptera	0.08 ± 0.05
Lycosidae	0.08 ± 0.05
Oligochaeta	0.89 ± 0.21
Overall geometric mean	0.14

a. Data from Ainsworth (1990a).

Table J-7. TFs for antimony in small mammals.[a]

Taxonomic group	Mean TF
Short-tailed field vole	7.8×10^{-4}
Rabbit	3.4×10^{-3}
Common shrew	6.0×10^{-3}
Overall mean	2.5×10^{-3}

a. Data from Ainsworth (1990a).

Table J-8. Summary of cadmium uptake factors and estimated TFs in terrestrial ecosystems.

Taxonomic Group	Geometric Mean Ratio of Tissue:Diet Cadmium Concentration (dry weight)[a]	TF
Herbivorous invertebrate	1.1	0.6
Carnivorous invertebrate	1.5	0.9
Detritivorous invertebrate	2.4	7.1[b]
Small mammal (*S. araneus*)	1.7	1.9

a. Data from Laskowski (1991).

b. Derived from a regression equation (Ma 1983) as discussed in text.

This value is in good agreement with TFs for other herbivorous invertebrates reported subsequently (e.g., Lindqvist 1992; Janssen and Hogervorst 1993).

TFs for cadmium in earthworms and other detritivores are typically higher than those for other soil macroinvertebrates. Uptake by earthworms has been shown to be dependent on many soil parameters, especially pH (Ma 1982), as well as the presence of other metals in the soil (Beyer et al. 1982). Data for earthworms were reviewed by Romijn et al. (1991), who observed that the TF is not constant but is inversely related to soil concentration. Thus, less cadmium is taken up relative to soil concentrations as concentrations increase. Ma (1982) defined the relationship between soil and worm concentrations of cadmium as:

$$ln(\,[\,Cadmium\,]\ in\ worm\ tissue) = 5.538 + 0.664\, ln([\,Cadmium\,]\ in\ soil\,) - 0.40\ pH \tag{J-2}$$

$$Earthworm_{BAF\ cadmium} = \frac{[Cadmium]\ in\ worm\ tissue}{[Cadmium]\ in\ soil} \tag{J-3}$$

Given the pH ranges identified at the INEEL facility (Martin et al. 1992) and the concentrations of cadmium in the soil (2.2 mg/kg), the earthworm TFs developed using this equation will range from approximately 4.5 to 7.0.

Assuming that carnivorous invertebrates consume primarily herbivorous species, a TF of 0.9 can be estimated for carnivorous insects by multiplying the estimated TF for these prey items (0.6) by the mean ratio of cadmium concentrations in carnivores and herbivores (1.5) reported by Laskowski (1991):

$$Carnivorous\ Invertebrate_{BAF\ cadmium} = BAF\ herbivores\ x \frac{[Cadmium]\ in\ carnivores}{[Cadmium]\ in\ prey} \tag{J-4}$$

Interspecific variation in cadmium accumulation among mammalian species in the same environment has been observed in several studies (e.g., Anthony and Kozlowski 1982; Scanlon 1987). Data appear to be most abundant for the shrew, which also typically has higher tissue concentrations than herbivorous/omnivorous small mammals (Hunter et al. 1987). Assuming that the TF of organisms consumed by shrews is approximately 1.1 (the geometric mean of values derived in the equation for carnivorous invertebrates), and the ratio of shrew body burden to prey body burden is 1.7 (Laskowski 1991), a shrew TF can be calculated by multiplying these two factors:

$$Shrew_{BAF\ cadmium} = BAF\ prey\ x \frac{[Cadmium]\ in\ shrew}{[Cadmium]\ in\ prey} \tag{J-5}$$

Thus, the TF for cadmium in small mammals is conservatively estimated as 1.9.

J-1.5.1.3 Chromium. Trivalent chromium is an essential trace element found in all living organisms. Chromium deficiency may result in irreversible metabolic damage. Several researchers have observed that chromium is biominified rather than biomagnified in terrestrial ecosystems. Indeed, in every example reported, chromium concentrations in animals were equal to or lower than those in soils and dietary items (reviewed by Outridge and Scheuhammer 1993). For example, chromium was the least accumulated of eight metals examined by Ma (1982) in earthworms, with a geometric mean of only 0.06 (chromium species not reported). In a recent study, TFs for earthworms were observed to be concentration-dependent (Van Gestel et al. 1993). Further, Beyer et al. (1990) observed no relationship between chromium concentrations in soil and biota at disposal facilities for dredged material. The validity of TFs derived in the absence of significant correlation is questionable. Such observations indicate that, as expected, chromium uptake is tightly regulated, and is unlikely to be significantly accumulated in the food chain.

In the absence of more definitive data, a TF of 0.06 is recommended for invertebrates shown in Table J-9. Because earthworms generally accumulate metals more avidly than other invertebrates, this value is likely to be conservative for soil-dwelling arthropods.

For small mammals, a TF of 6×10^{-5} has been estimated (VanHorn et al. 1995) as the product of the assimilation efficiency of ingested hexavalent ^{51}Cr in cotton rats (0.008; Taylor and Parr 1978) and the PUF for chromium (0.0075; Baes et al. 1984). However, because assimilation efficiency refers to dose absorption (i.e., bioavailability) rather than bioaccumulation, this manipulation is inappropriate. The geometric mean TF for chromium in the house mouse (*Mus musculus*) (0.2) determined by Beyer et al. (1990) is shown in Table J-10.

J-1.5.1.4 Copper. Laskowski (1991) summarized available data on copper bioaccumulation in terrestrial food chains. Organisms considered included macroinvertebrates and the carnivorous shrew (S. araneus), and encompassed four trophic levels: herbivores, carnivores, top carnivores, and detritivores. Of 37 reported tissue: dietary concentration ratios identified in the literature for copper, 22 were greater than 1.0 (Laskowsi 1991). Geometric mean values for herbivorous, carnivorous, and detritivorous invertebrates were 2.5, 1.1, and 0.3, respectively. The mean tissue: diet ratio for the shrew was 0.2 (Laskowski 1991). However, the slope of the regression line of dietary to tissue concentrations for all species was less than 1.0 (0.83), suggesting regulation of copper ion concentrations in terrestrial organisms. These data, summarized in Table J-10, were used to estimate the following TFs for terrestrial organisms.

The bioavailability of copper to earthworms appears to be strongly influenced by copper concentration and soil type, but not by soil pH (Ma 1982; Ma et al. 1983; Corp and Morgan 1991). As for cadmium and other metals, less copper is taken up relative to soil concentrations as these concentrations increase. Ma et al. (1983) defined the relationship between tissue and soil concentrations of copper in soil (in mg/kg dry weight) near a zinc smelter as:

$$[Copper]\ in\ worm\ tissue = 14.88 + 0.344\ x\ [Copper]\ in\ soil \qquad (J\text{-}6)$$

$$Earthworm_{BAF_{copper}} = \frac{[Copper]\ in\ worm\ tissue}{[Copper]\ in\ soil} \qquad (J\text{-}7)$$

showing the decreasing TF with increasing soil concentration. Corp and Morgan (1991) observed a similar relationship in worms exposed to naturally metalliferous soils. In addition, concentration-dependence of the copper TF for isopods was recently reported (Hopkin et al. 1993). This relationship can be used to calculate site-specific TFs for copper in earthworms. This formula yields TFs for earthworms of around 6 for soil concentrations of 1 to 10 mg/kg, 0.9 for 10 to 100 mg/kg, and 0.4 for 100 to 1,000 mg/kg.

Table J-9. Geometric mean TFs for chromium in terrestrial ecosystems.

Taxonomic Group	TF
Earthworm, arthropod[a]	0.06
Small mammal (*Mus musculus*)[b]	0.20

a. Data from Ma (1982).

b. Data from Beyer et al. (1990).

Table J-10. Summary of copper uptake factors and estimated TFs in terrestrial ecosystems.

Taxonomic Group	Geometric Mean Ratio of Tissue: Diet Copper Concentration (dry weight)[a]	TF
Herbivorous invertebrate	2.5	1.0
Carnivorous invertebrate	1.1	1.1
Detritivorous invertebrate	0.3	0.34[b]
Small mammal (*S. araneus*)	0.2	0.2

a. Data from Laskowski (1991).

b. Calculated using regression equation from Ma et al. (1983).

Assuming a PUF of 0.4 for copper (Baes et al. 1984), a mean tissue:soil TF of 1.0 can be estimated for herbivorous invertebrates by multiplying this factor by the ratio of copper in animal:plant tissues (2.5):

$$Herbivorous\ Invertebrate_{BAF\ copper} = PUF_{copper}\ x\ \frac{[Copper]\ in\ invertebrates}{[Copper]\ in\ plants} \tag{J-8}$$

This value is in good agreement with subsequently reported TFs for copper in other herbivorous invertebrates (e.g., Lindqvist 1992; Janssen and Hogervorst 1993). Assuming that carnivorous invertebrates consume primarily herbivorous species, a TF of 1.1 can be estimated for carnivorous insects by multiplying the estimated TF for these prey items (1.0) by the geometric mean ratio of copper concentrations in carnivores and herbivores (1.1) reported by Laskowski (1991):

$$Carnivorous\ Invertebrate_{BAF\ copper} = BAF_{herbivores}\ x\ \frac{[Copper]\ in\ carnivores}{[Copper]\ in\ prey} \tag{J-9}$$

This value is somewhat higher than reported in other studies (e.g., Beyer et al. 1990; Janssen and Hogervorst 1993).

Assuming that the TF of organisms consumed by shrews is approximately 1.1 (the geometric mean of values derived above for herbivorous and carnivorous macroinvertebrates), and the ratio of shrew body burden to prey body burden is 0.2 (Laskowski 1991), a shrew TF can be calculated by multiplying these two factors:

$$Shrew_{BAF\,copper} = BAF_{prey} \, x \, \frac{[Copper] \text{ in shrew}}{[Copper] \text{ in prey}} \tag{J-10}$$

Thus, the TF for copper in shrews is around 0.2 as listed in Table J-10. This TF agrees with a TF value estimated for house mice by Beyer et al. (1990).

J-1.5.1.5 Lead. Soil pH and CEC are prime factors in predicting the uptake and accumulation of lead in earthworms (e.g., Ma 1982). Organic matter, calcium, and the presence of other metals are also influential (Terhivuo et al. 1994). In most surveys, the lead TF for earthworms exceeds unity only when pH is low (Terhivuo et al. 1994). As for other metals, lead TFs are typically lower in highly polluted soil. In addition to soil-specific factors, prediction of TFs for lead in earthworms is complicated by the existence of significant interspecific differences among earthworms exposed to the same soils (Terhivuo et al. 1994).

Ma et al. (1983) and Corp and Morgan (1991) have developed regression equations for predicting lead TFs in earthworms. However, the equations supporting their data are dependent on pH, organic matter, and calcium concentration. Data on these characteristics are presently lacking for INEEL soils. Until they are available, the following equation from Corp and Morgan (1991), which requires pH and concentration of lead in soil and provides a good fit to the data ($r^2 = 93.3$) may be used:

$$\log [Lead]_{worm} = 2.65 + 0.897 \, x \log [Lead]_{soil} - 3.56 \, x \log pH \tag{J-11}$$

$$Earthworm_{BAF\,lead} = \frac{[Lead] \text{ in worm tissue}}{[Lead] \text{ in soil}} \tag{J-12}$$

As shown in Table J-11, given the pH ranges identified at the INEEL (Martin et al. 1992) and the concentrations of lead in the soil (13 to 72 mg/kg), the earthworm TFs developed using this equation will range from 0.05 up to 0.23.

Values derived from this equation agree well with field data reported by Beyer et al. (1990) (0.27 to 0.32 at soil lead concentrations of 21 to 336 mg/kg dry weight).

Hopkin et al. (1993) developed regression equations for lead uptake in the terrestrial woodlice (isopods) *Porcellio scaber* and *Oniscus asellus*. The following equation for *O. asellus* yields slightly higher TFs, and so is recommended as conservative for use at INEEL:

$$\log [Lead]_{arthropod} = 0.842 \, x \log [Lead]_{soil} - 0.507 \tag{J-13}$$

$$Arthropod_{BAF\,lead} = \frac{[Lead] \text{ in arthropod}}{[Lead] \text{ in soil}} \tag{J-14}$$

Given the concentrations of lead in the soil the arthropod TFs developed using this equation will range up to 0.290 (in mg/kg dry weight). These TF values agree with field data reported by Janssen and Hogervorst (1993) (0.01 to 0.43).

Tissue concentrations of lead in insectivorous small mammals generally correlate better with ambient lead concentrations and are higher than those of herbivores (e.g., Beardsley et al. 1978; Ma 1987;

Table J-11. TFs for lead in terrestrial ecosystems.

Taxonomic Group	TF
Earthworm	0.18[a]
Arthropod	0.29[b]
Small mammal (*Talpa europea*)[c]	0.6

a. Regression equation from Corp and Morgan (1991) as discussed in text. Soil pH values at various locations on the INEEL ranged from 5.25 to 8.78 (Martin et al. 1992).

b. Regression equation from Hopkin et al. (1993) as discussed in text.

c. Based on the geometric mean kidney:soil lead ratio reported by Ma (1987).

Ma et al. 1991). A geometric mean lead TF of 0.08 for the house mouse *M. musculus* can be calculated from the Beyer et al. (1990) data. Whole-body TFs were not located for insectivorous small mammals, but geometric mean TFs of 0.6 and 0.2 were calculated for lead in kidney and liver of the mole *Talpa europea* (Ma 1987). Lead concentrations in these tissues were much higher in the shrew (*S. araneus*) than the vole (*M. agrestis*) from the same area (Ma et al. 1991). In the absence of more specifically applicable data, a highly conservative small mammal TF for lead can be estimated as 0.6 based on the kidney:soil ratio calculated from Ma's (1987) data. A TF was used for all functional groups to be protective.

J-1.5.1.6 Mercury. Large differences in both bioconcentration and toxicity of organic and inorganic mercury have been observed in aquatic ecosystems. While methylation of inorganic mercury by methanogenic bacteria is common in aquatic sediments and greatly facilitates metal uptake, the degree of methylation occurring in terrestrial environments is unclear. The mercury present at INEEL was conservatively considered to be entirely organic for purposes of TRV development. To avoid overconservatism, mercury in INEEL soils will be considered to be inorganic for purposes of TF development.

Romijn et al. (1991) used available data to calculate a geometric mean TF of 0.4 for inorganic mercury in earthworms. This value also provides a conservative estimate of TF for other soil-dwelling macroinvertebrates.

Little information regarding bioaccumulation of mercury by other organisms was located. Bull et al. (1977) examined concentrations of mercury in various tissues of woodmice (*Apodemus sylvaticus L.*) and bank voles (*Clethrionomys glareolus Schr.*) collected near a chloralkali plant (mercury contamination ranges of 0.69 to 12.6 mg/kg dry weight) and in an uncontaminated reference area (mercury concentration ranged from 0.04 to 0.19 mg/kg dry weight). As observed with other metals, the TFs were considerably higher in the control than in the affected area, i.e., uptake decreased with increasing ambient concentration.

Because mercury concentrations in certain areas of INEEL are greater than background, TFs calculated in the Bull et al. (1977) study (as summarized in Table J-12) will be used in this analysis. TFs for the woodmouse tissues ranged from 0.3 in liver to 1.3 in muscle, while those in bank voles ranged from 0.2 in brain to 1.2 in hair. Geometric mean TFs calculated for all tissues examined were 0.7 and 0.4 for woodmice and bank voles, respectively, will be used for the appropriate INEEL receptors.

Table J-12. Mean TFs for mercury in small mammal tissues.[a]

Tissue	TFs	
	Woodmouse	Bank Vole
Brain	0.7	0.2
Hair	1	1.2
Kidney	0.7	0.5
Liver	0.3	0.2
Muscle	1.3	0.4
Geometric mean	0.7	0.4

a. Data from Bull et al. (1977).

J-1.5.1.7 Zinc. Like chromium and copper, zinc is an essential trace element for many organisms. As a result, it has received relatively little attention as a potential ecological toxicant in terrestrial ecosystems. Estimated TFs for zinc in macroinvertebrates and small mammals are presented in Table J-13.

As reported for other metals, zinc TFs in earthworms appear to be inversely dependent on soil concentration. Van Gestel et al. (1993) reported that the earthworm (*Eisenia andrei*) was able to regulate its body concentration of zinc (around 100 mg zinc/kg tissue) at soil concentrations up to 560 mg/kg. Higher "maintenance" levels in tissues were observed in other species (e.g., Ma et al. 1983; Kruse and Barrett 1985; Beyer et al. 1990). Like cadmium, zinc uptake by earthworms is influenced by soil pH (Ma et al. 1983; Corp and Morgan 1991). However, the available regression equations do not adequately reflect the regulation of zinc concentration evident in field data from several sources. Van Gestel et al. (1993) reported a zinc TF of 72 at a soil zinc concentration of 1.4 mg/kg. At soil zinc concentrations of approximately 90 to 100, Van Gestel's (1993) and Beyer's groups (1990) reported TFs of around 1.3. Similarly, TFs of approximately 0.2 were observed by both groups at soil zinc concentrations of 560 to 570 mg/kg. Zinc TFs for earthworms should be selected from these ranges on the basis of site-specific soil concentrations (Table J-13).

Several authors have shown a negative dependence of zinc TF on soil concentrations in arthropods as well (Lindqvist 1992; Janssen and Hogervorst 1993; Hopkin et al. 1993). The regression equations developed by Hopkin et al. (1993) for the terrestrial woodlice (isopods *P. scaber* and *O. asellus*) are representative of these data. The equation for *P. scaber* yields slightly higher TFs:

$$\log\,[Zinc\,]_{arthropod} = 0.274 \times \log\,[Zinc\,]_{soil} + 1.890 \qquad \text{(J-15)}$$

$$Arthropod_{\,BAF\,zinc} = \frac{[Zinc]\ in\ arthropod}{[Zinc]\ in\ soil} \qquad \text{(J-16)}$$

As shown in Table J-13, given the concentrations of zinc in the soil, the arthropod TFs developed using this equation will range up to 0.83 (in mg/kg dry weight).

Table J-13. TFs for zinc in terrestrial ecosystems.

Taxonomic Group	TF
Earthworm[a]	
~ 1 mg/kg zinc in soil	72
~100 mg/kg zinc in soil	1.3
~500 mg/kg zinc in soil	0.2
Arthropod	0.83[b]
Small mammal[c]	0.7

a. Data from Beyer et al. (1990) and van Gestel et al. (1993).

b. Calculated using the regression equation from Hopkin et al. (1993), as discussed in text.

c. Data from Beyer et al. (1990).

A study of zinc accumulation in the organs of granivorous and insectivorous small mammals exposed to sewage sludge containing high concentrations of zinc (and other metals), showed some increase with exposure but no pathological effects (Hegstrom and West 1989). Beyer et al. (1990) reported TFs for the house mouse (*M. musculus*) of 0.4 to 1.2 exposed to soil concentrations of 74 to 240 mg/kg, with a general trend of inverse relationship to soil concentration. The geometric mean of these data, 0.7, is recommended for use at INEEL where soil concentrations are compatible (Table J-13). Data are presently lacking to evaluate TFs at higher soil concentrations. The homeostatic regulation of zinc in most organisms suggests that TFs will decrease at higher soil concentrations.

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